Aspects of Theoretical Neutrino Physics

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Workshop on Fundamental Physics at the Intensity Frontier
Nov 30–Dec 2, 2011 in Rockville, MD

Fermilab

Outline

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1. Understanding particle masses and mixing angles
2. Leptonic CP violation and Leptogenesis
3. Neutrinos and nuclear physics
4. Neutrinos as a window to the “dark sector”
5. Neutrinos as astrophysical messengers
6. Conclusions

Understanding particle masses and mixing angles

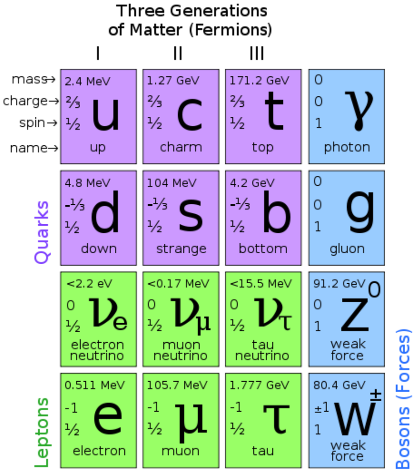
What is the origin of the
three-family structure in the Standard Model?

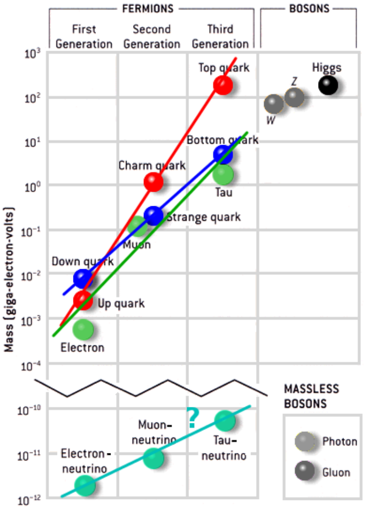
Why are quark mixing angles
so different from lepton mixing angles?

How do neutrinos get their mass?

Understanding particle masses and mixing angles

Looking at the Standard Model, we see a lot of unexplained structure.





Understanding particle masses and mixing angles

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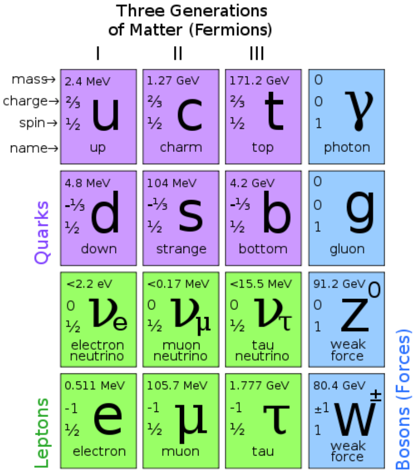
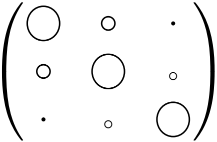
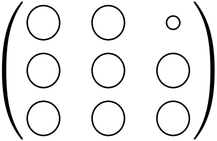


Quark mixing:

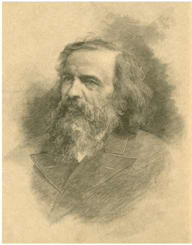


Lepton mixing:



The Periodic Table in 1870

I	II	III	IV	V	VI	VII	VIII		
H 1.01									
Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
K 39.1 Cu 63.5	Ca 40.1 Zn 65.4		Ti 47.9	V 50.9 As 74.9	Cr 52.0 Se 79.0	Mn 54.9 Br 79.9	Fe 55.9	Co 58.9	Ni 58.7
Rb 85.5 Ag 108	Sr 87.6 Cd 112	Y 88.9 In 115	Zr 91.2 Sn 119	Nb 92.9 Sb 122	Mo 95.9 Te 128	I 127	Ru 101	Rh 103	Pd 106
Ce 133 Au 197	Ba 137 Hg 201	La 139 Ti 204	Pb 207	Ta 181 Bi 209	W 184		Os 194	Ir 192	Pt 195
			Th 232		U 238				



Dmitri Mendeleev

Understanding particle masses and mixing angles (2)

Fermion mass generation in the Standard Model

$$\mathcal{L}_{\text{mass}} \supset Y_u^{\alpha\beta} \frac{v}{\sqrt{2}} \bar{u}_{\alpha L} u_{\beta R} + Y_d^{\alpha\beta} \frac{v}{\sqrt{2}} \bar{d}_{\alpha L} d_{\beta R} + Y_\ell^{\alpha\beta} \frac{v}{\sqrt{2}} \bar{\ell}_{\alpha L} \ell_{\beta R}$$

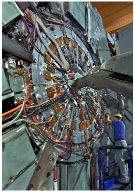
$$+ \text{ neutrino mass terms}$$

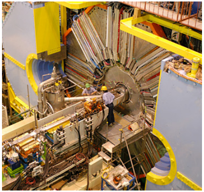
- We think we understand the origin of $v/\sqrt{2}$: Higgs vev
  - Energy Frontier: Look for the Higgs
- We have no idea where the structure in $Y_u^{\alpha\beta}$, $Y_d^{\alpha\beta}$, $Y_\ell^{\alpha\beta}$ comes from.
  - Intensity Frontier: Precision measurements to uncover more of the underlying structure (e.g. quark–lepton complementarity)
  - Intensity Frontier: Look for new physics with non-trivial flavor dynamics
  - Intensity Frontier: Elucidate mechanism of neutrino mass generation
- See talks by Mu-Chun Chen and Tao Han
- See experimental talks

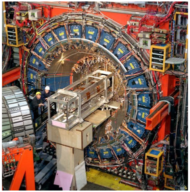
Understanding particle masses and mixing angles (3)

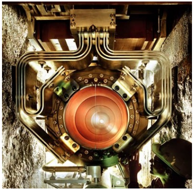
Quark sector:

- *b*, *c*, *K* factories
- Rare decay searches
- Meson oscillations
- . . .









Lepton sector:

- Neutrino oscillations
  (Mixing angles and mass squared differences)
- Direct neutrino mass measurements
  (Hierarchical vs. quasi-degenerate mass schemes)
- Neutrinoless double beta decay
  (Majorana vs. Dirac mass term)
- Charged lepton flavor violation searches
- Astrophysics and cosmology
- . . .

Outline

Leptonic CP violation and Leptogenesis

What is the origin of the
cosmic matter–antimatter asymmetry?

Is the CP symmetry violated
only for quarks or also for leptons?

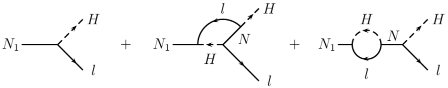
Leptogenesis

A mechanism for generating a cosmic matter–antimatter asymmetry

- Assume a seesaw model for neutrino mass generation

$$-\mathcal{L}_{\text{seesaw}} \supset Y_\nu^{\alpha\beta}\, \bar{\ell}_{\alpha L} \tilde{H} N_{\beta R} \;+\; \frac{1}{2} M_R^{\alpha\beta}\, \overline{N^c_{\alpha R}} N_{\beta R}$$

- Heavy right-handed neutrinos N_R decay out of thermal equilibrium via $N_{1R} \to H + \ell$



- If $Y_\nu^{\alpha\beta}$ is complex (CP violating), we can have

$$\varepsilon = \frac{\Gamma(N_{1R} \to H\ell) - \Gamma(N_{1R} \to H^* \bar{\ell})}{\Gamma(N_{1R} \to H\ell) + \Gamma(N_{1R} \to H^* \bar{\ell})} \neq 0$$

- Electroweak sphalerons ($\Delta(B+L) = 6$) convert lepton asymmetry into baryon asymmetry

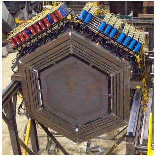
By the seesaw formula $m_\nu = v^2/2 \times Y_\nu^* M_R^{-1} Y_\nu^T$, complex Y_ν implies CP violation in low-energy observables like neutrino oscillations (barring fine-tuned cancellations) $\to$ talk by Boris Kayser

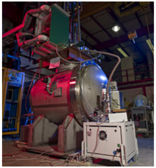
Outline

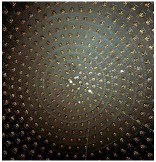
Neutrinos and nuclear physics

How do neutrinos interact with matter?

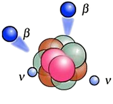
Neutrinos and nuclear physics

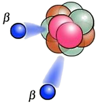






- Neutrino scattering on nuclear targets
  - Among the weakest known interactions in particle physics
  - Probed from MeV to > TeV energies
  - Of particular interest is the $\mathcal{O}$(GeV) region, where quasi-elastic scattering (possibly modified by nuclear effects), resonance production and deep-inelastic scattering contribute.
  - Nuclear physics models accurate to $\mathcal{O}(10\%)$
  - Data from many different target materials will help improve our understanding of nuclear physics at these energies
  - A crucial ingredient for oscillation experiments
  - See talks by Josh Spitz, Dave Schmitz, Bill Louis
- Matrix elements for neutrinoless double beta decay
  - Required for measurement of neutrino mass in $0\nu2\beta$ decay
  - Current uncertaintes are $O(1)$
  - Data on both $0\nu2\beta$ and $2\nu2\beta$ decay can teach us a lot about nuclear structure
  - See talks by S. Elliot, J. Wodin, H. Robertson





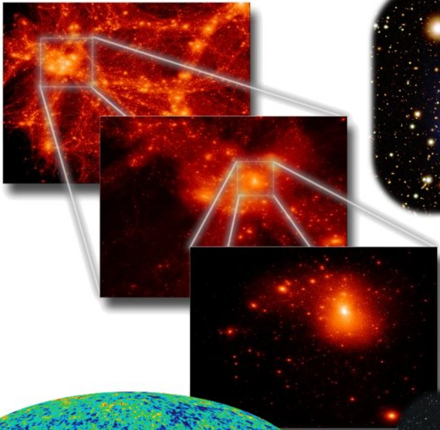
Outline

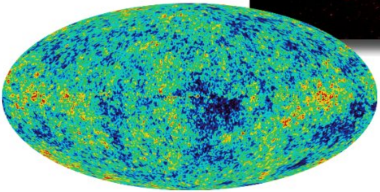
Neutrinos as a window to a “dark sector”

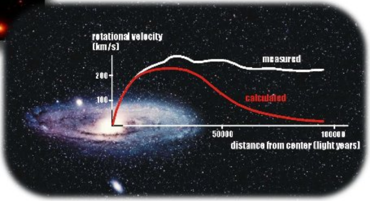
Are there $SU(3) \times SU(2) \times U(1)$-singlet particles?

If so, what are their properties?

Evidence for dark matter

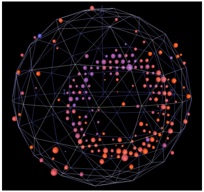


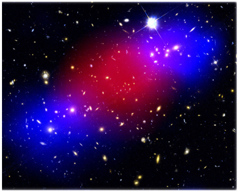




Neutrinos as a window to a “dark sector”

- Are there $SU(3) \times SU(2) \times U(1)$-singlet particles?
  - YES! Lots of evidence for Dark Matter
- Are there other “dark” particles?
  - A dark sector with many SM singlets?
  - New “dark” gauge forces?
- Neutrinos could mix with such singlet particles
  - Oscillations into light sterile neutrinos
  - Production of heavier sterile neutrinos in a neutrino production target



Outline

Neutrinos and astrophysics

How do supernovae work?

How do neutrinos behave under extreme conditions?

What are the properties of dark matter?

How and where are cosmic rays accelerated?

Neutrinos and supernovae

- We want to learn about supernovae
  - Matter under extreme conditions
  - Origin of heavy elements
  - ...
- Neutrinos are crucial for the explosion mechanism
- But: Neutrino propagation through a supernova is highly non-trivial and poorly understood
  - Self-induced MSW type matter effects
  - Collective oscillations
  - ...

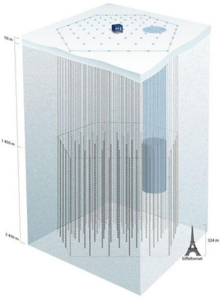
  These are *Standard Model* phenomena!
  — New physics would make things even more complicated
- Detecting supernova neutrinos can teach us about particle physics, astrophysics, and cosmology
- See talk by Alex Friedland

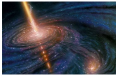
SN1987A: Kamiokande-II paper has 979 citations, 1 Nobel Prize

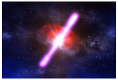
Neutrinos as astrophysical messengers

Neutrinos from dark matter annihilation

- DM capture and annihilation in the Sun
- Annihilation products usually involve neutrinos
- From these, we can learn about dark matter physics and neutrino physics





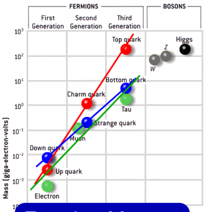


Neutrinos from cosmic ray sources

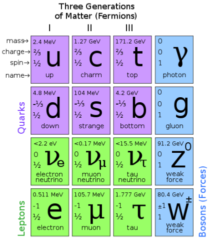
- Gamma ray bursts
- Supernova remnants
- Active Galactic Nuclei
- Microquasars

Outline

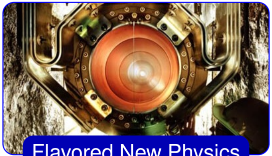
Conclusions: Neutrinos can tell us about . . .

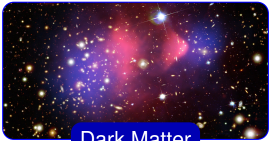


Fermion Masses

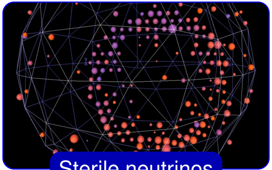


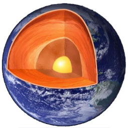
The Origin of Flavor

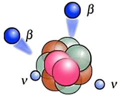

Flavored New Physics


Dark Matter

Leptogenesis


Sterile neutrinos


The Earth



Nuclei


Cosmic Rays


Supernovae

Thank you!